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APPENDIX B

Second Edition

Modern Control Engineering

Katsuhiko Ogata

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Second Edition

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PART I Basic Analysis of Control Systems by Conventional and State-Space Methods

CHAPTER 1

Introduction to Control Systems Analysis

1-1 INTRODUCTION

Automatic control has played a vital role in the advance of engineering and science. In addition to its extreme importance in space-vehicle systems, missile-guidance systems, aircraft-autopiloting systems, robotic systems, and the like, automatic control has become an important and integral part of modern manufacturing and industrial processes. For example, automatic control is essential in the numerical control of machine tools in the manufacturing industries. It is also essential in such industrial operations as controlling pressure, temperature, humidity, viscosity, and flow in process industries.

Since advances in the theory and practice of automatic control provide the means for attaining optimal performance of dynamic systems, improving productivity, relieving the drudgery of many routine repetitive manual operations, and more, most engineers and scientists must now have a good understanding of this field.

Historical review. The first significant work in automatic control was James Watt's centrifugal governor for the speed control of a steam engine in the eighteenth century. Other significant works in the early stages of development of control theory were due to Minorsky, Hazen, and Nyquist, among many others. In 1922, Minorsky worked on automatic controllers for steering ships and showed how stability could be determined from the differential equations describing the system. In 1932, Nyquist developed a relatively simple procedure for determining the stability of closed-loop systems on the basis of open-loop response to steady-state sinusoidal inputs. In 1934 Hazen, who introduced the term servomechanisms for position control systems, discussed the design of relay servomechanisms capable of closely following a changing input.

During the decade of the 1940s, frequency-response methods made it possible for engineers to design linear closed-loop control systems that satisfied performance requirements. From the end of the 1940s to early 1950s, the root-locus method due to Evans was fully developed.

The frequency-response and root-locus methods, which are the core of classical control theory, lead to systems that are stable and satisfy a set of more or less arbitrary performance requirements. Such systems are, in general, acceptable but not optimal in any meaningful sense. Since the late 1950s, the emphasis in control design problems has been shifted from the design of one of many systems that work to the design of one optimal system in some meaningful sense.

As modern plants with many inputs and outputs become more and more complex, the description of a modern control system requires a large number of equations. Classical control theory, which deals only with single-input, single-output systems, becomes powerless for multiple-input, multiple-output systems. Since about 1960, because the availability of digital computers made possible time-domain analysis of complex systems, modern control theory, based on time-domain analysis and synthesis using state variables, has been developed to cope with the increased complexity of modern plants and the stringent requirements on accuracy, weight, and cost in military, space, and industrial applications.

Recent developments in modern control theory are in the field of optimal control of both deterministic and stochastic systems, as well as the adaptive and learning control of complex systems. Now that digital computers have become cheaper and more compact, they are used as integral parts of these control systems. Recent applications of modern control theory include such nonengineering systems as biological, biomedical, economic, and socioeconomic systems.

Definitions. The *controlled* variable is the quantity or condition that is measured and controlled. The *manipulated* variable is the quantity or condition that is varied by the controller so as to affect the value of the controlled variable. Normally, the controlled variable is the output of the system. *Control* means measuring the value of the controlled variable of the system and applying the manipulated variable to the system to correct or limit deviation of the measured value from a desired value.

In studying control engineering, we need to define additional terms that are necessary to describe control systems, such as plants, disturbances, feedback control, and feedback control systems. In what follows, definitions of these terms are given. Then a description of closed-loop and open-loop control systems follows and the advantages and disadvantages of closed-loop and open-loop control systems are compared. Finally, definitions of adaptive and learning control systems are given.

Plants. A plant is a piece of equipment, perhaps just a set of machine parts functioning together, the purpose of which is to perform a particular operation. In this book, we shall call any physical object to be controlled (such as a heating furnace, a chemical reactor, or a spacecraft) a *plant*.

Processes. The *Merriam-Webster Dictionary* defines a process to be a natural, progressively continuing operation or development marked by a series of gradual changes that succeed one another in a relatively fixed way and lead toward a particular result or end; or an artificial or voluntary, progressively continuing operation that consists of a series of controlled actions or movements systematically directed toward a particular result or end.

In this book we shall call any operation to be controlled a *process*. Examples are chemical, economic, and biological processes.

Systems. A system is a combination of components that act together and perform a certain objective. A system is not limited to physical ones. The concept of the system can be applied to abstract, dynamic phenomena such as those encountered in economics. The word system should, therefore, be interpreted to imply physical, biological, economic, and the like, systems.

Disturbances. A disturbance is a signal that tends to adversely affect the value of the output of a system. If a disturbance is generated within the system, it is called *internal*, while an *external* disturbance is generated outside the system and is an input.

Feedback Control. Feedback control refers to an operation that, in the presence of disturbances, tends to reduce the difference between the output of a system and some reference input and that does so on the basis of this difference. Here only unpredictable disturbances are so specified, since predictable or known disturbances can always be compensated for within the system.

Feedback Control Systems. A system that maintains a prescribed relationship between the output and some reference input by comparing them and using the difference as a means of control is called a *feedback control system*. An example would be a room-temperature control system. By measuring the actual room temperature and comparing it with the reference temperature (desired temperature), the thermostat turns the heating or cooling equipment on or off in such a way as to ensure that the room temperature remains at a comfortable level regardless of outside conditions.

Feedback control systems are not limited to engineering but can be found in various nonengineering fields as well. The human body, for instance, is a highly advanced feedback control system. Both body temperature and blood pressure are kept constant by means of physiological feedback. In fact, feedback performs a vital function: It makes the human body relatively insensitive to external disturbances, thus enabling it to function properly in a changing environment.

As another example, consider the control of automobile speed by a human operator. The driver decides on an appropriate speed for the situation, which may be the posted speed limit on the road or highway involved. This speed acts as the reference speed. The driver observes the actual speed by looking at the speedometer. If he is traveling too slowly, he depresses the accelerator and the car speeds up. If the actual speed is too high, he releases the pressure on the accelerator and the car slows down. This is a feedback control system with a human operator. The human operator here can easily be replaced by a mechanical, electrical, or similar device. Instead of the driver observing the speedometer, an electric generator can be used to produce a voltage that is proportional to the speed. This voltage can be compared with a reference voltage that corresponds to the desired speed. The difference in the voltages can then be used as the error signal to position the throttle to increase or decrease the speed as needed.

Servo Systems. A servo system (or servomechanism) is a feedback control system in which the output is some mechanical position, velocity, or acceleration. Therefore, the terms servo system and position- (or velocity- or acceleration-) control system are synonymous. Servo systems are extensively used in modern industry. For example, the completely automatic



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